Search for Invisible Decays of a Dark Photon Produced in e^+e^- Collisions at BaBar

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Overview

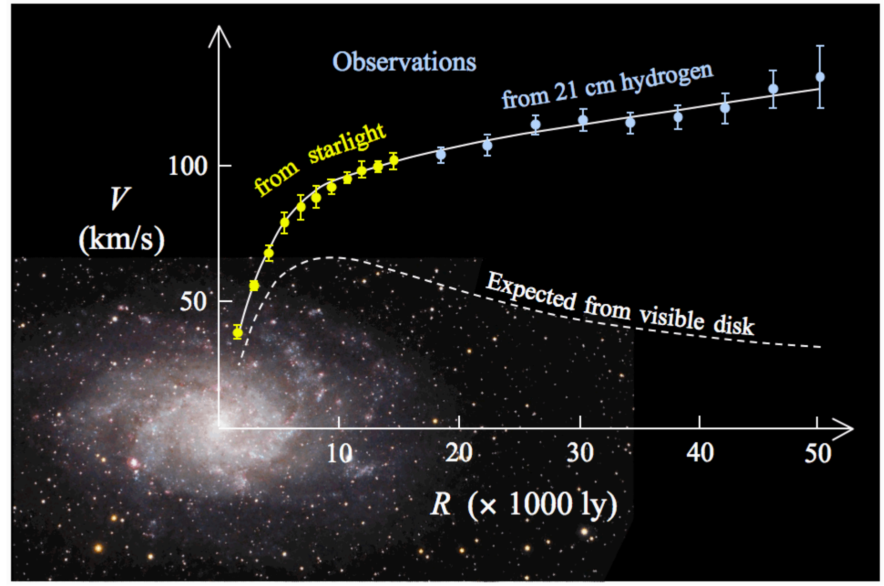
- “Search for invisible decays of a dark photon produced in e^+e^- collisions at BaBar”

  arXiv:1702.03327 [hep-ex]

We search for single-photon events in 53 fb^{-1} of e^+e^- collision data collected with the *BABAR* detector at the PEP-II B-factory. We look for events with a single high-energy photon and a large missing momentum and energy, consistent with production of a spin-1 particle A' through the process $e^+e^- \to \gamma A'$; $A' \to$ invisible. Such particles, referred to as “dark photons”, are motivated by theories applying a $U(1)$ gauge symmetry to dark matter. We find no evidence for such processes and set 90% confidence level upper limits on the coupling strength of A' to e^+e^- in the mass range $m_{A'} \leq 8$ GeV. In particular, our limits exclude the values of the A' coupling suggested by the dark-photon interpretation of the muon $(g-2)_\mu$ anomaly, as well as a broad range of parameters for the dark-sector models.

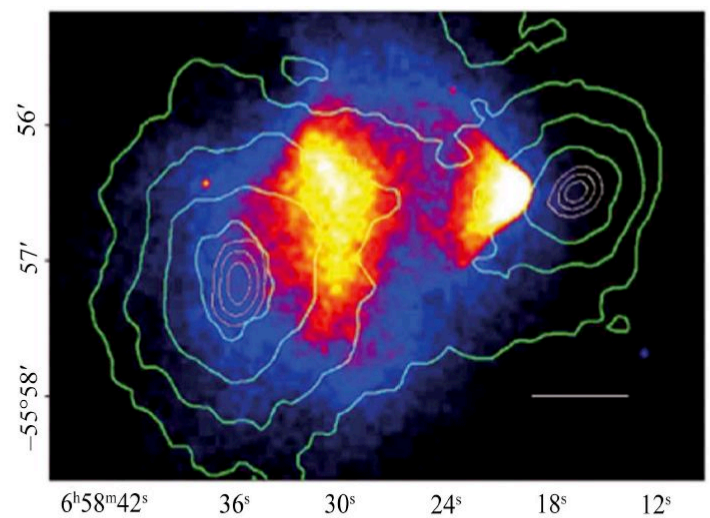
Dark Matter And Dark Sectors

- So far, we have only been able to infer the existence of dark matter through its gravitational effects
    - Null results from direct detection experiments and the LHC motivate the exploration of ideas beyond the standard WIMP paradigm, such as the possibility of light dark sectors



M33 Rotation Curves

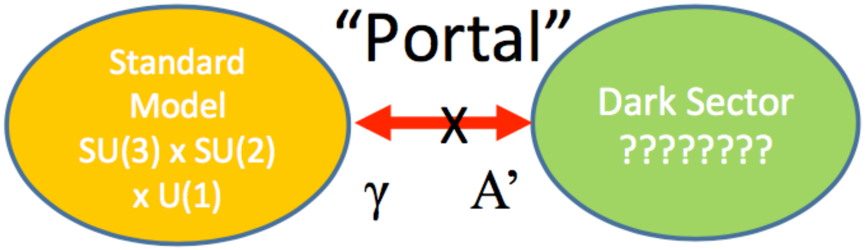
- These dark sectors would contain particles that don't couple directly to the SM
    - Theoretical motivation comes from string theory and many other BSM scenarios that include an extra U(1) symmetry
    - Dark matter could be a part of a dark sector and may consist of more than one dark sector particle
    - Furthermore, such a dark sector could have a rich structure beyond the particle(s) we refer to as dark matter



Bullet Cluster Weak Lensing

Motivation

- Models have proposed a low-mass spin-1 "dark photon" that is the gauge boson of a new U(1) symmetry and couples to both the SM and the dark sector
- These dark photons could be in the MeV to GeV mass range and could mix with the SM photon with mixing strength ϵ



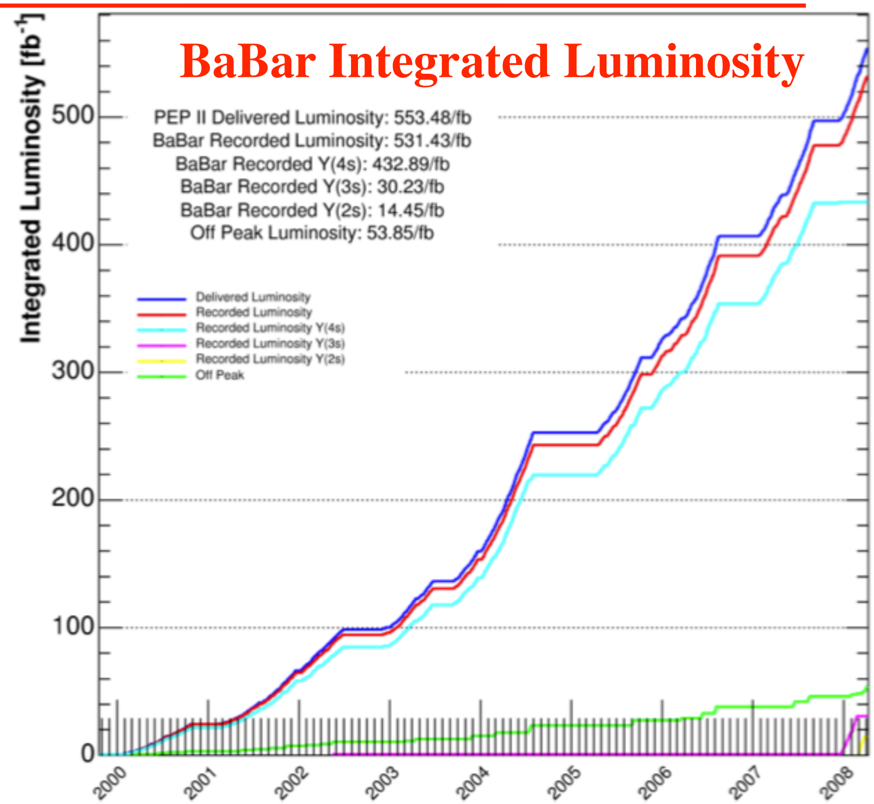
- The dark photon (A') could:
  - Decay to SM fermions if other DM states are inaccessible. This would produce visible decays
  - Decay to a lighter dark matter state χ. If $m_\chi < m_{A'}/2$, then the dominant decay mode of the A' would then be invisible: $A' \to \chi\overline{\chi}$
- Could explain phenomena such as the proton charge radius puzzle and the muon $(g\text{-}2)_\mu$ anomaly:

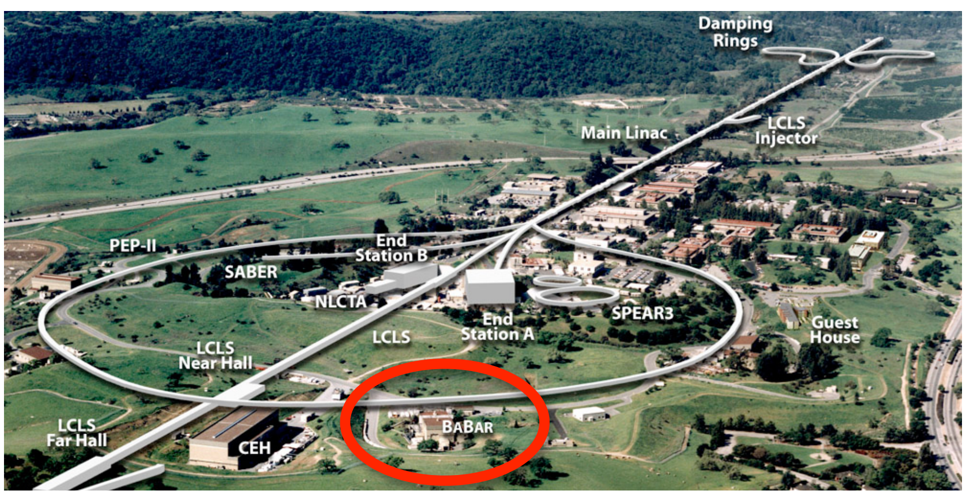
Phys. Rev. D 73, 072003 (2006)

$$g_\mu(\mathrm{Exp}) \stackrel{?}{=} g_\mu(\mathrm{SM}) + g_\mu(A')$$

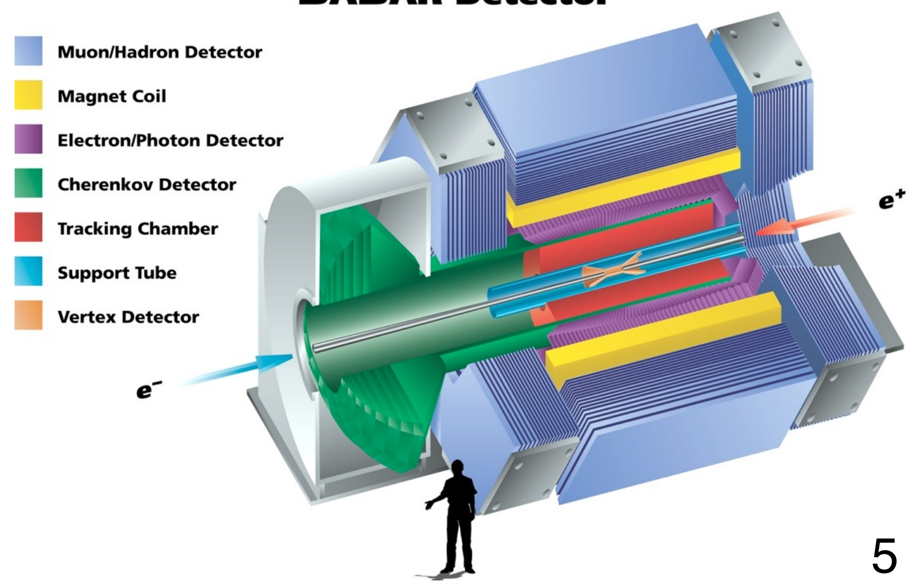
The BaBar Experiment

- Data collected by the BaBar detector at Stanford Linear Accelerator Center
- Asymmetric-energy e^+ and e^- beams
- Designed to be a B factory, operating primarily at $\Upsilon(4S)$ resonance, producing 470×10^6 $B\overline{B}$ pairs
- This analysis uses $53\ \mathrm{fb}^{-1}$ collected at center-of-mass (CM) energies at/near the $\Upsilon(nS)$ $(n = 2, 3, 4)$ resonances with a special “single photon” trigger



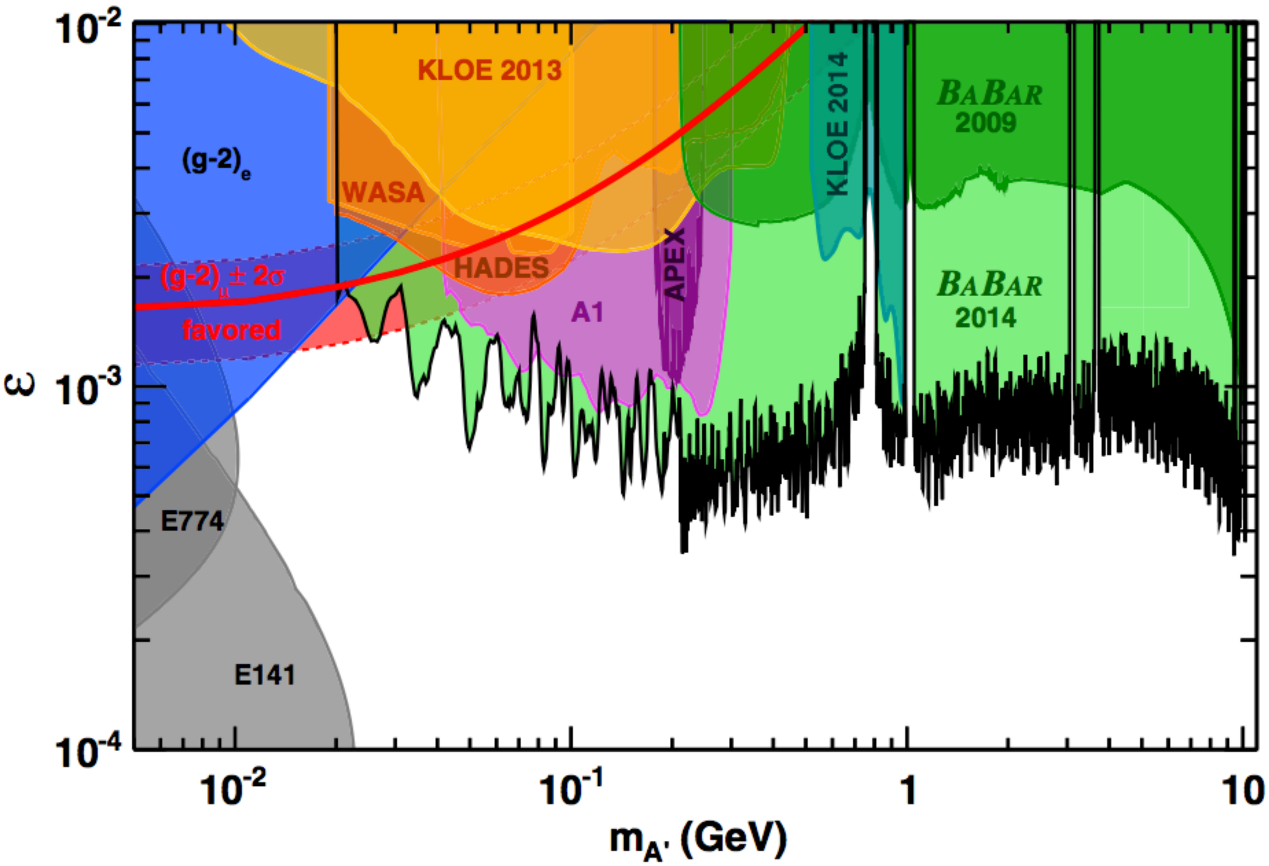


BABAR Detector



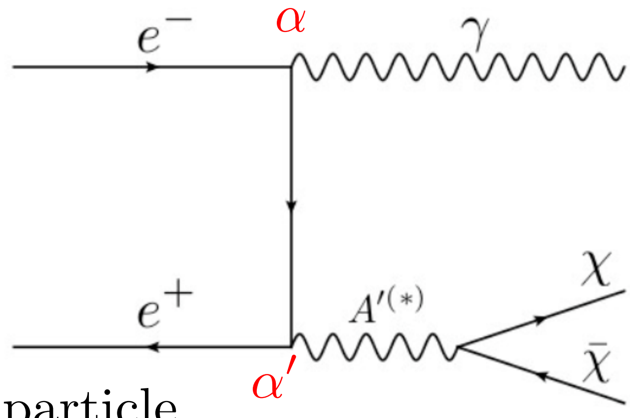
Previous A' Search

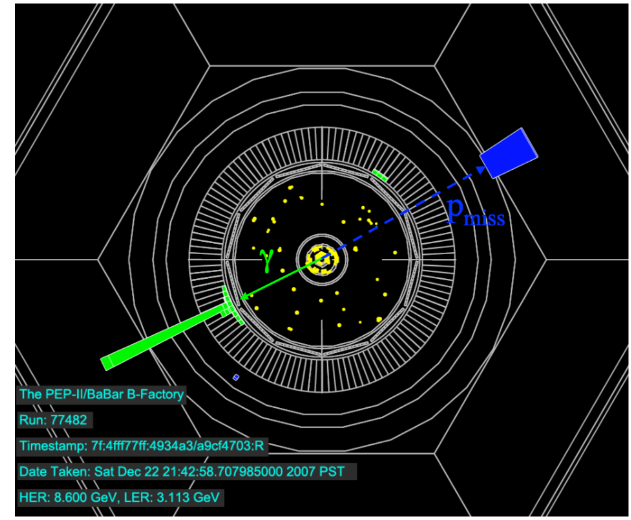
- BaBar previously searched for visible $A' \to \ell^+\ell^-$ $(\ell = e, \mu)$ decays in $e^+e^- \to \gamma A'$ using $516\ \text{fb}^{-1}$ **Phys. Rev. Lett. 113, 201801 (2014)**
- Search covered the mass range $0.02\ \text{GeV} < m_{A'} < 10.2\ \text{GeV}$
- No significant signal observed
- Placed 90% C.L. upper limit on mixing strength ϵ at the level of $\sim 10^{-4} - 10^{-3}$



Invisible Decay Search

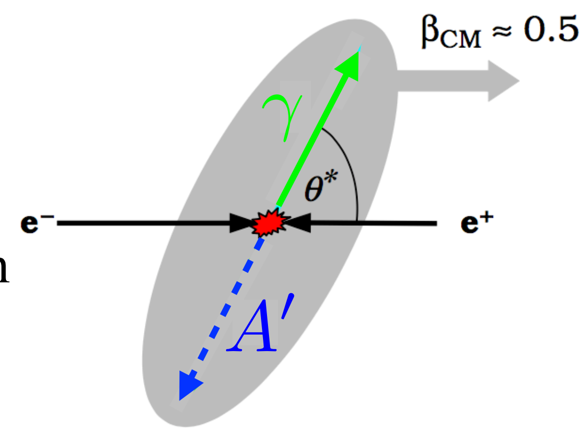
- The present analysis searches for the A’ in $e^+e^- \to \gamma A'$ events where the A’ decays undetectably:





$\alpha' = \epsilon^2\alpha$
χ = undetectable DM particle

- Signature: monochromatic photon and missing energy/mass
- Reconstruct missing mass squared, $M_X^2 = s - 2E_\gamma^*\sqrt{s}$
- Assumptions:



  - A’ width is negligible compared to experimental resolution
  - A’ decays predominantly to dark matter
  - Either there is a single A’ state in the range $0 < m_{A'} < 8$ GeV or, if there is more than one, they do not interfere
  - Do not expect A’ production to be affected by the presence of Υ resonances

Single-Photon Trigger

- Detection requires dedicated single-photon trigger:
  - Level-1 Hardware trigger: 1 or more calorimeter clusters with $E_{LAB} > 0.8$ GeV
  - Level-3 Software trigger: Two different software triggers were used:

Low M_X

- Require $E^*_\gamma > 2$ GeV
- No tracks originating from e^+e^- interaction region
- Trigger active for full 53 fb^{-1} data sample

High M_X

- Require $E^*_\gamma > 1$ GeV
- No tracks originating from e^+e^- interaction region
- Trigger active for 35.9 fb^{-1} subset of 53 fb^{-1} data sample

	Low Mass	High Mass
$\Upsilon(4S)$	$5.9\,fb^{-1}$	----
$\Upsilon(3S)$	$28\,fb^{-1}$	$20\,fb^{-1}$
$\Upsilon(2S)$	$14.4\,fb^{-1}$	$14.4\,fb^{-1}$
off-peak	$4.2\,fb^{-1}$	$1.5\,fb^{-1}$
Total	$53\,fb^{-1}$	$35.9\,fb^{-1}$

$$E^*_\gamma = \frac{s - M_X^2}{2\sqrt{s}}$$

Event Selection

$\Upsilon(3S)$ $\Upsilon(2S)$

Low Mx

$-4\ \mathrm{GeV}^2 < M_X^2 < 36\ \mathrm{GeV}^2$

- Dominant Background from $e^+e^- \to \gamma\gamma$ events where a photon escapes detection
- 1 Electromagnetic Calorimeter (EMC) cluster
- Require $E_\gamma^* > 3\ \mathrm{GeV}$
- No drift chamber tracks with momentum $p^* > 1\ \mathrm{GeV}$
- Multivariate discriminator cut

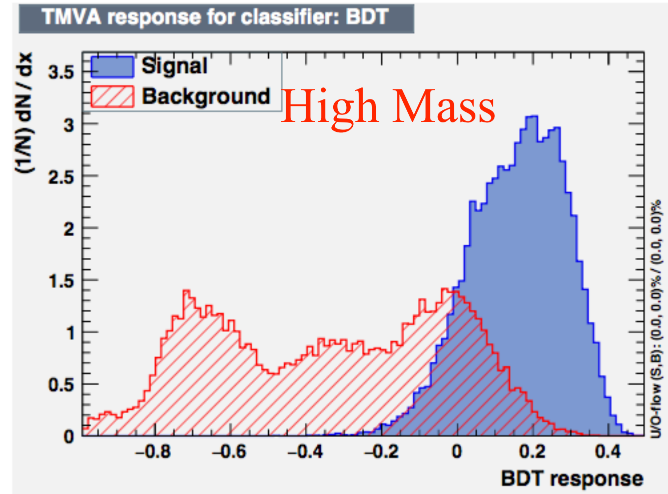
High Mx

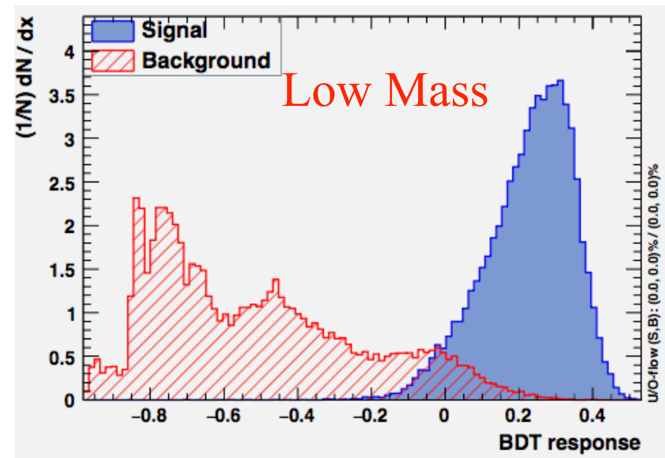
$24\ \mathrm{GeV}^2 < M_X^2 < 69\ (63.5)\ \mathrm{GeV}^2$

- Dominant background from radiative Bhabha events ($e^+e^- \to e^+e^-\gamma$) where the electron and positron escape detection
- 1 EMC cluster with transverse profile consistent with an electromagnetic shower
- Require $E_\gamma^* > 1.5\ \mathrm{GeV}$
- No drift chamber tracks with momentum $p^* > 0.1\ \mathrm{GeV}$
- Multivariate discriminator cut

Multivariate Selection

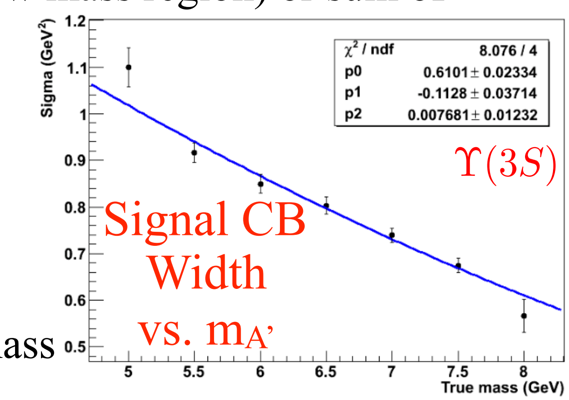
- Apply additional selection criterion using Boosted Decision Tree (BDT) multivariate discriminator
- The BDT is trained separately for the Low Mass and High Mass samples
- 12 discriminating variables including:
  - Shape parameters for the most energetic EMC cluster
  - Total EMC energy without the most energetic cluster
  - E^*, θ^*, and $\Delta\phi^*(E_1)$ of the second most energetic EMC cluster
  - E^*, θ^*, and $\Delta\phi^*(E_1)$ of the Instrumented Flux Return (IFR) cluster closest to the missing momentum direction
- Train using:
  - 25k simulated signal events with uniformly distributed A' masses
  - 25k background events from the $\Upsilon(3S)$ sample





Signal Extraction I

- Optimize event selection to minimize the expected upper limit on the $e^+e^- \to \gamma A'$ cross section $\sigma_{A'}$
- Use A' mass and BDT output to subdivide data samples
  - Low m$_{A'}$ ($m_{A'} < 5.5$ GeV): 3 BDT selection criteria (Loose Signal, Tight Signal, Background) applied to $\Upsilon(2S)$, $\Upsilon(3S)$, and $\Upsilon(4S)$ samples
  - High m$_{A'}$ ($5.5 < m_{A'} < 8$ GeV): 2 BDT selection criteria (Loose Signal, Background) applied to $\Upsilon(2S)$ and $\Upsilon(3S)$ samples
  - Note: The Low M_X dataset includes Low $m_{A'}$ and High $m_{A'}$ bins, while the High M_X dataset only includes a High $m_{A'}$ bin
- Signal extraction from missing mass distribution:
  - Background distribution:
    - Taken from data with -0.5 < BDT < 0
    - Crystal Ball function (peaking bkg) plus 2nd order polynomial (low mass region) or sum of exponentiated polynomials (high mass region)
  - Signal Distribution:
    - Taken from high statistics simulation
    - Crystal Ball (CB) function with its width dependent on missing mass

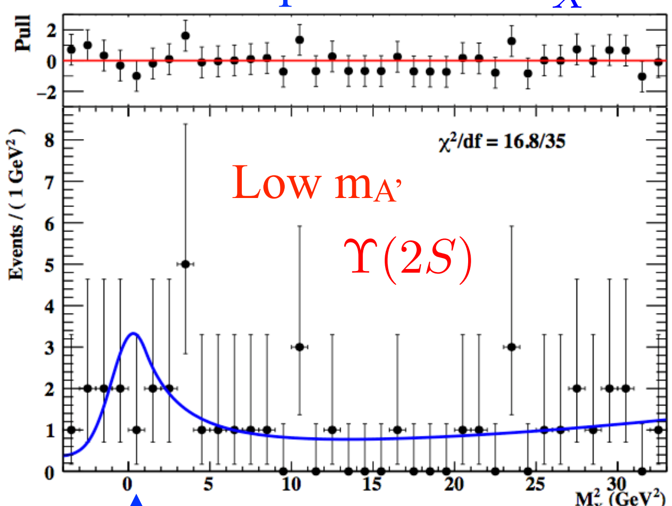


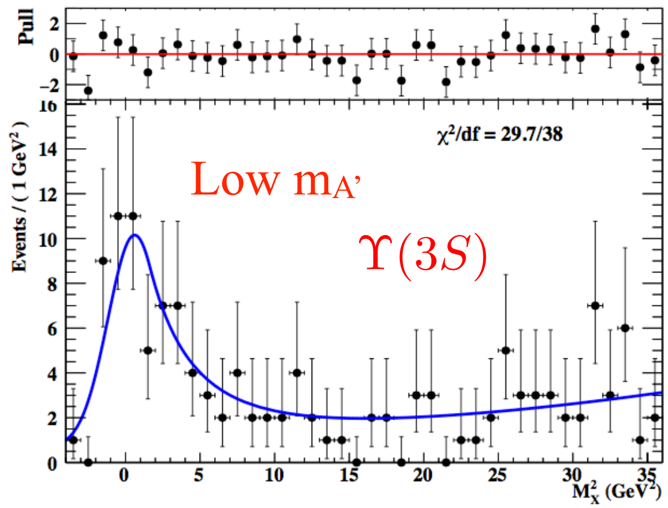
Signal Extraction II

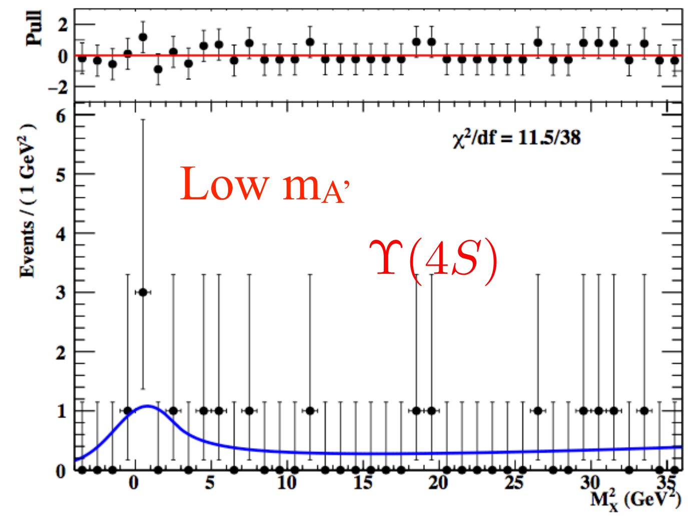
- Extract yields in simultaneous unbinned maximum likelihood fit to:
  - 9 independent samples in Low m$_{A'}$ region
  - 4 independent samples in High m$_{A'}$ region

Dataset	"lowM"				"highM"		
Dataset	$\mathcal{L}$	Selection			$\mathcal{L}$	Selection	
		$\mathcal{R}_B$	$\mathcal{R}_L'$	$\mathcal{R}_T$		$\mathcal{R}_B$	$\mathcal{R}_L$
$\Upsilon(2S)$	15.9 fb^{-1}	22,590	42	6	15.9 fb^{-1}	405,441	324
$\Upsilon(3S)$	31.2 fb^{-1}	68,476	129	26	22.3 fb^{-1}	719,623	696
$\Upsilon(4S)$	5.9 fb^{-1}	7,893	16	9			

- Example fits to M_X^2 distributions:

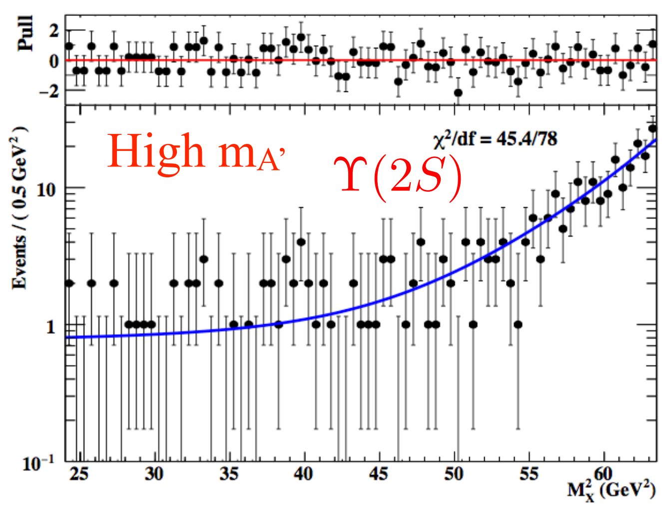


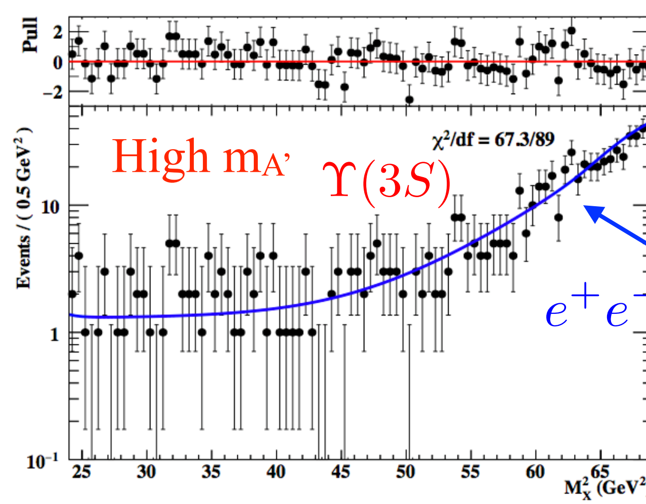




$e^+e^- \to \gamma\gamma$

= Bkg only fit



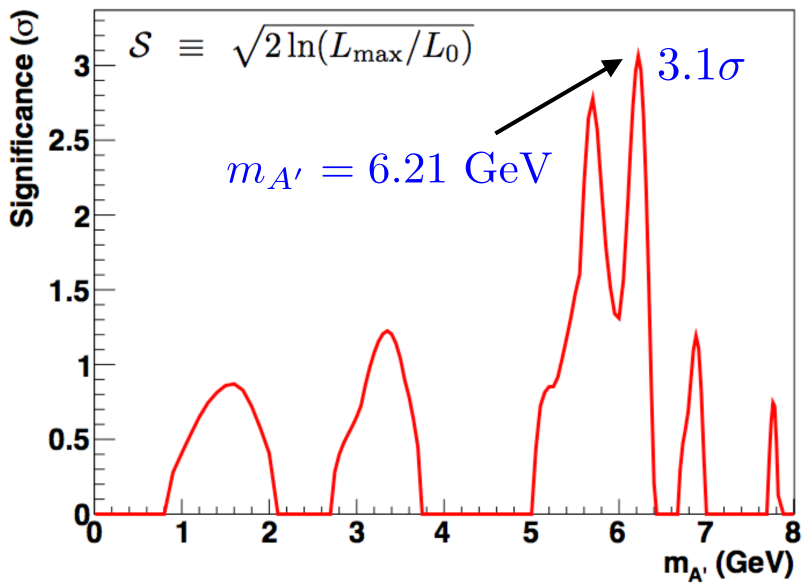


$e^+e^- \to e^+e^-\gamma$

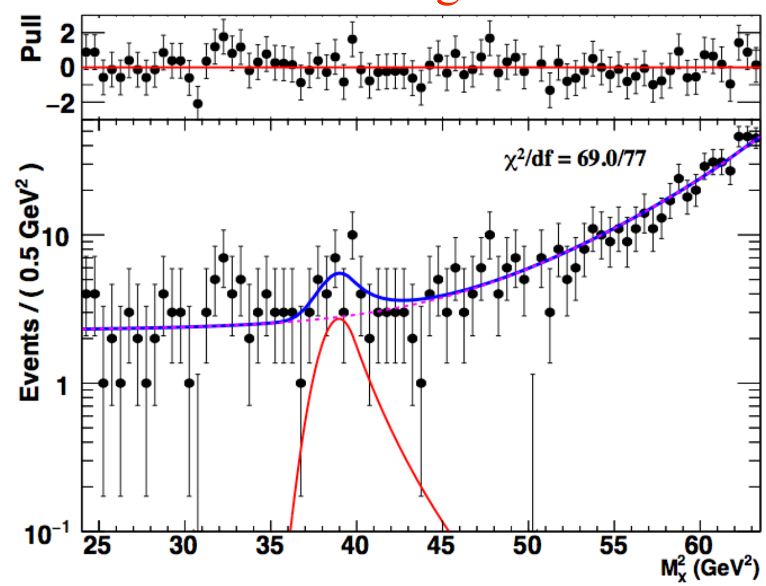
Significance Scan

- Scan $m_{A'}$ between 0 and 8 GeV in 166 steps (step size is approximately half the mass resolution)

Local Signal Significance



Missing Mass Fit With
Max Local Significance



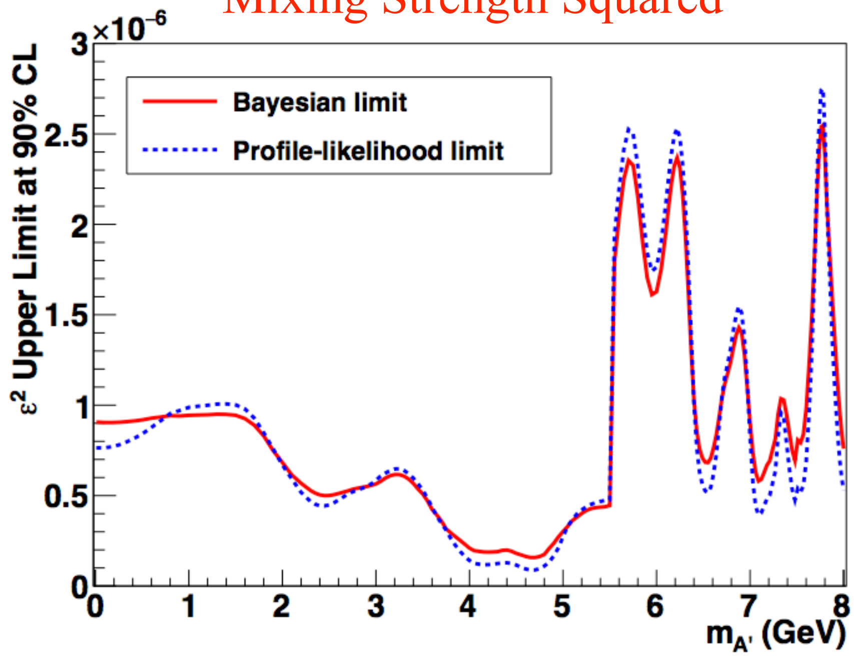
- Highest signal significance for $m_{A'} = 6.21$ GeV

$$S_{\text{local}} = 3.1\sigma \quad S_{\text{global}} = 2.6\sigma$$

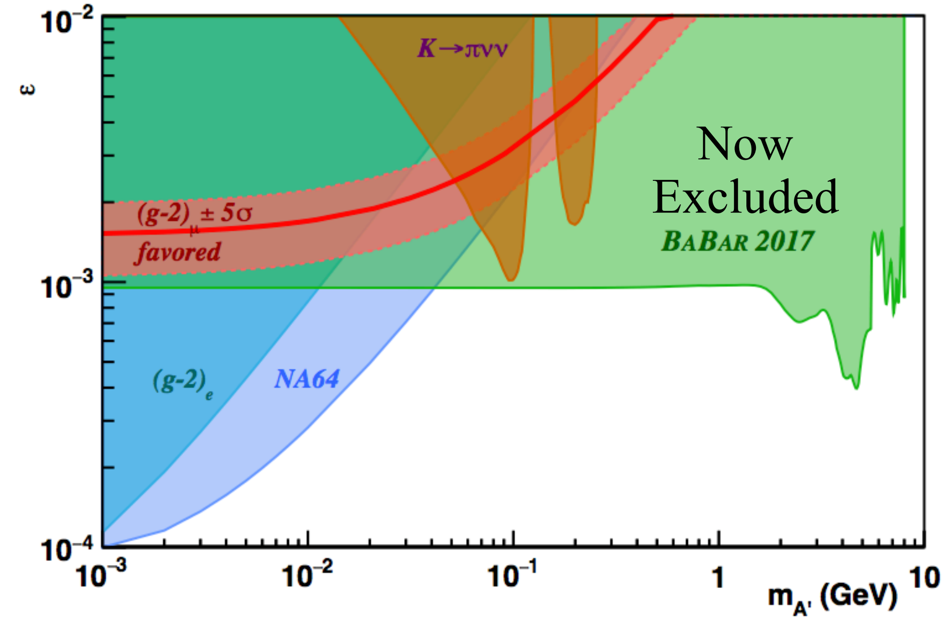
Upper Limits

- As we see no significant signal, we set upper limits on the mixing parameter ϵ as a function of $m_{A'}$

90% CL Upper Limits on
Mixing Strength Squared



Mixing Strength vs. A' Mass



- With our new measurement, we can rule out the dark photon as an explanation for the $(g-2)_\mu$ anomaly

Summary

- We have performed a search for invisible decays of a dark photon A' in $e^+e^- \to \gamma A'$ events arXiv:1702.03327 [hep-ex]
  - No significant signal is observed, with the highest significance corresponding to $m_{A'} = 6.21$ GeV with $\sigma_{\mathrm{global}} = 2.6$
- In the absence of an observation, we place 90% CL upper limits on the dark photon mixing parameter ϵ in the region $m_{A'} < 8$ GeV
  - The region of A' parameter space favored by the $(g\text{-}2)_\mu$ anomaly has now been excluded by searches for visible and invisible decay channels
  - Our limits are a significant improvement over previous results and constrain dark-sector models across a broad region of A' parameter space
- BaBar is continuing to search for a dark photon decaying to visible states